Achieving High Pressure Shock Hugoniot Measurements in Cylindrical Geometry Utilizing a High-Explosive Pulsed Power Drive

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Abstract

ALT-3 (Advanced Liner Technology) is a collaboration between VNIIEF and LANL that aims to conduct high velocity material experiments and measure shock velocities at pressures near 1 TPa. The DEMG (Disk Explosive Magnetic Generator) is used to drive a >60MA current that accelerates an aluminum liner to speeds in excess of 20 km/s. A simple circuit model is presented that models the DEMG to reasonable accuracy and is then coupled with 1-D magnetohydrodynamic simulations of both the liner and target. 2-D hydrodynamic simulations of the target are also presented along with implications for measurement accuracy and expected results.

I. BACKGROUND

In continuing collaboration with Russian scientists at VNIIEF, ALT-3 is a joint project designed to accelerate an aluminum liner to extremely high velocities and study the application of cylindrically imploded liners to shock physics and making highly accurate Hugoniot measurements. The Russian-made DEMG (Disk Explosive Magnetic Generator) will be able to achieve extremely high currents with as much as 70 MA usable for driving a z-pinch experiment. In this experiment, LANL will fabricate a high-precision liner and target and will field numerous diagnostics for the experiment that will be tentatively conducted in Russia during the spring or summer of 2012. The liner will be accelerated to near 20 km/s and impacted into a target where shock and free surface velocities will be measured in order to extract Hugoniot data at pressures near 1 TPa. Similar experiments have been proposed for the ATLAS pulsed power machine[1], and flyer experiments in an expanding geometry have been conducted on the Sandia Z Pulsed Power Machine[2].

II. EXPERIMENTAL OBJECTIVES

There are three main technical objectives in the initial ALT-3 experiment:

A. Characterize DEMG Performance

Of primal importance is the characterization and evaluation of the DEMG for use in pulsed power experiments. Specifically, this experiment will demonstrate the ability of the DEMG to provide a large and fast current pulse for use in driving a liner implosion experiment to extremely high velocities.

B. Assess Performance of Aluminum Liners at High Velocities

This experiment will also examine the performance of the aluminum liner in a high-current, high velocity z-pinch experiment The stability of the liner as well as long-wavelength non-uniformities on the inner surface of the liner will also be examined.

C. Assess Feasibility of Making Highly Accurate Hugoniot Measurements

The final experimental objective is to determine the feasibility of conducting a shock Hugoniot experiment utilizing a pulsed power drive in an imploding geometry. The converging cylindrical geometry of the z-pinch experiment presents unique challenges that will determine whether an accurate measurement of important shock quantities can be made.

III. EXPERIMENT SETUP

The ALT-3 experiment will comprise of a VNIIEF-supplied disk generator driving a LANL-supplied aluminum liner into a LANL aluminum target. PDV probes fielded by LANL will be used to collect velocimetry data from a central measurement unit (CMU) positioned along the axis of the experiment. The velocimetry data will be collected from 32 different PDV channels viewing the target itself and also the liner via holes in the target. Liner performance will be characterized by assessing uniformity of shock breakout along the target surface as well as azimuthal symmetry in the liner probes. The target will be partially stepped with steps 0.7 mm, 0.6 mm, and 0.4 mm thick recessed into the 0.8-mm thick target. Current profiles in the generator and

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14. ABSTRACT
ALT-3 (Advanced Liner Technology) is a collaboration between VNIIEF and LANL that aims to conduct high velocity material experiments and measure shock velocities at pressures near 1 TPa. The DEMG (Disk Explosive Magnetic Generator) is used to drive a >60MA current that accelerates an aluminum liner to speeds in excess of 20 km/s. A simple circuit model is presented that models the DEMG to reasonable accuracy and is then coupled with 1-D magnetohydrodynamic simulations of both the liner and target. 2-D hydrodynamic simulations of the target are also presented along with implications for measurement accuracy and expected results.

15. SUBJECT TERMS

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load will be measured using a combination of Faraday rotation probes and B-dot induction coils. A preliminary drawing of the experimental setup is presented in Figure 1, showing a portion of the transmission line, liner, target, and CMU. The right side is a rotational axis of symmetry.

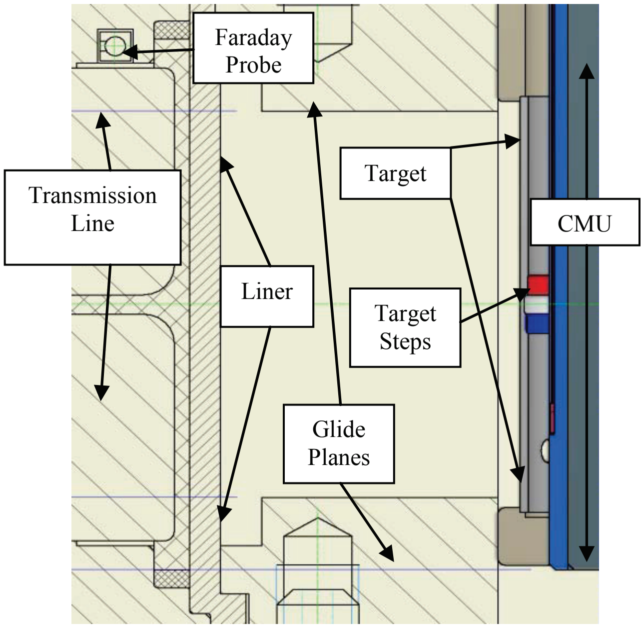

Figure 1. Current ALT-3 liner and target assembly (rotationally symmetric about the right side).

The DEMG (Disk Explosive Magnetic Generator) is a flux compression generator utilizing modular disks of copper and HE that when detonated, compresses the flux between disks and then into a load. Currents in the DEMG can reach as much as 100 MA and through a foil opening switch (FOS), approximately 60 MA can be delivered to a load over a period of 3.5 μs. A schematic drawing of the DEMG is shown in Figure 2, but the design for the ALT-3 experiment will have the radial portion of the transmission line at the same axial position as the liner load (Figure 1 is also rotated 90° counter-clockwise relative to Figure 2).

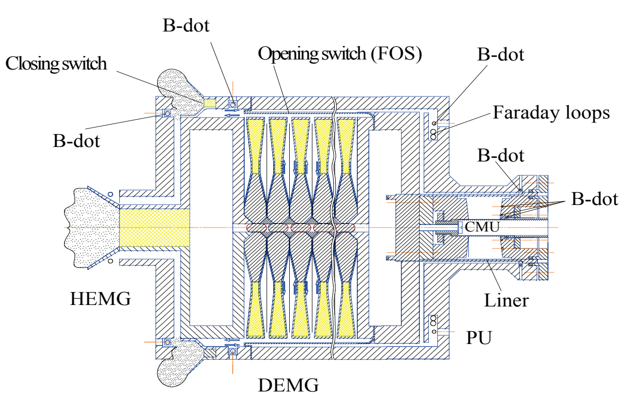

Figure 2. Schematic diagram of DEMG[3]

IV. DEMG SIMULATIONS

A ladder-network circuit model was used to simulate the DEMG using simple circuit elements. The flux compression of the DEMG was modeled using a time-varying inductance from Buyko et al[4]. The foil opening switch was approximated by a time-varying resistance extracted from the current and voltage profiles also presented by Buyko et al[3]. The circuit diagram showing this model is presented in Figure 3 and shows coupling between the circuit and the 1-D MHD simulation of the liner implosion load. The circuit is initially seeded with a 7MA current provided by the helical explosive magnetic generator (HEMG) that is upstream of the DEMG.

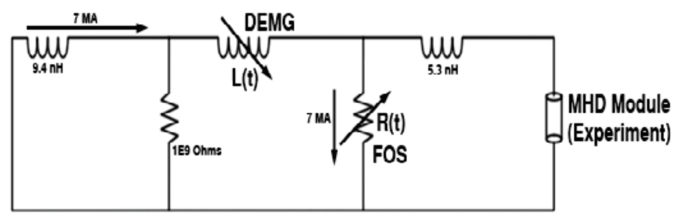

Figure 3. Circuit diagram used to approximate DEMG and FOS to be coupled with 1-D MHD simulations of the load.

For the actual experiment, it has been proposed to use an explosive closing switch (ECS) between the DEMG and the load in order to keep the load from experiencing the seed current before the ramp up to peak current. This will hopefully help improve liner stability. The results of our simple circuit model are compared to simulations presented by Buyko et al in Figure 4 and are found to be in good qualitative agreement.

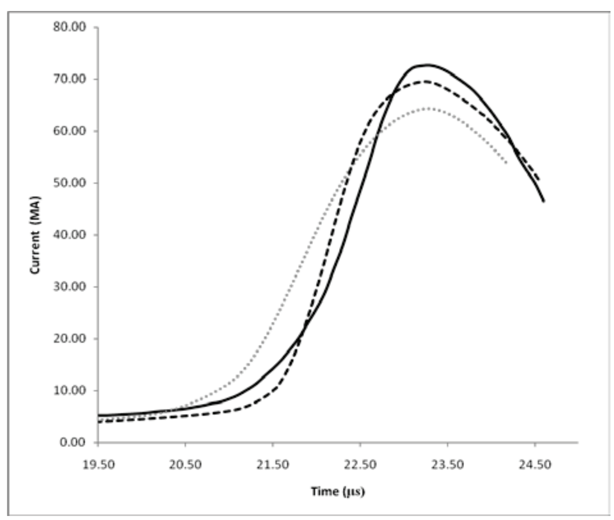

Figure 4. Current profiles compared to results reported by Buyko et al[3]. Solid line is from Bukyo, grey dotted line is a first attempt and the black dashed line is the final calculated current profile from the circuit model.

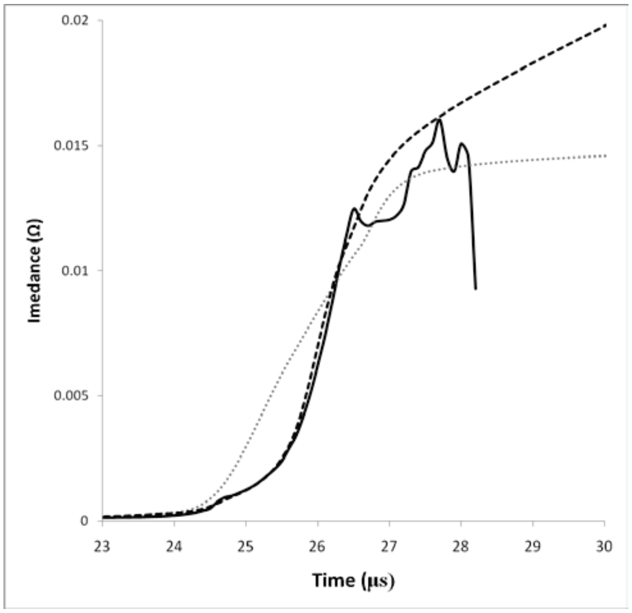

Figure 5. Fuse impedance as a function of time. The legend matches that in Figure 4 but the timescale is different.

From Figure 5 it is shown that the change in impedance over time is crucial to replicating the qualitative behavior of the fuse and replicating the current profile in the load regardless of the final impedance of the fuse. The integral of the current over time is representative of total energy delivered to the load and when calculated, it further highlights the qualitative similarity between the dashed and solid current profiles. The energy delivered to the load is extremely important for the accurate MHD simulation of the liner implosion, and this circuit model provides a more accurate representation of the dynamics of the system compared to using a programmed current profile in the MHD simulation.

V. ALUMINUM LINER SIMULATIONS

The aluminum liner for this experiment will be 4 cm in length, 3 mm in thickness, and will have an outer diameter of 4 cm. The selection of these dimensions ensures an impact velocity of at least 20 km/s as well as ensuring at least half of the liner remains solid. 1-D MHD simulations confirm that less than half of the liner will be molten at impact and that this should help to mitigate the effects of instability growth. The results of these simulations are presented in Figure 6 and Figure 7 showing the phase diagram of various parts of the liner and the velocity and radius traces of the liner surfaces respectively. From these figures, we see the outer surface of the liner expands rapidly at 23 µs which corresponds to peak current. The liner reaches a velocity of 23 km/s at impact but this may be an over-estimate as many factors are not accounted for in one dimension.

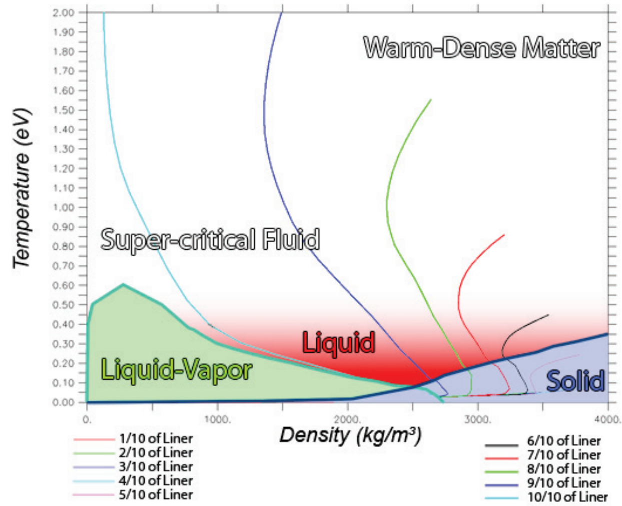

Figure 6. Temperature/density phase diagram of the liner. Each line represents a Lagrangian cell at 1/10th of the thickness of the initial liner from the outer surface (teal, left-most) to the inner surface (not visible). The phases are identified on the phase diagram.

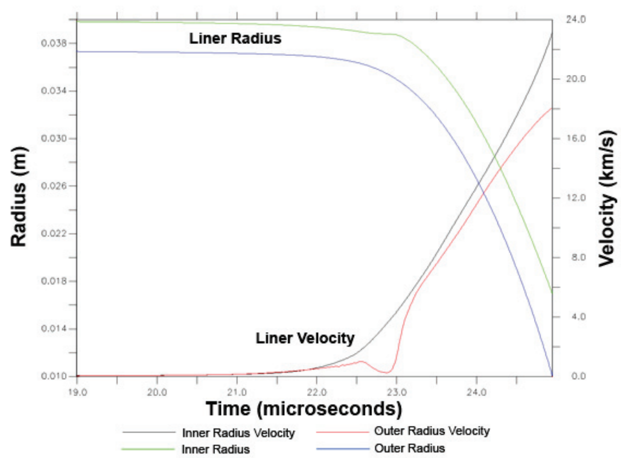

Figure 7. Radius and velocity diagram of the liner inner and outer surfaces from beginning of movement until impact.

Additional 2-D MHD simulations were done using a programmed current profile to try to characterize the inner surface of the liner during the implosion. The results of these simulations are presented in Figure 8 and show that a straight glide plane with a notch represents an appropriate glide plane configuration that minimizes perturbations along the inner surface of the liner during the z-pinch. This information is then used in 2-D hydrodynamic target simulations to characterize the inner surface of the impacter and analyze the effects of a non-uniform impact.

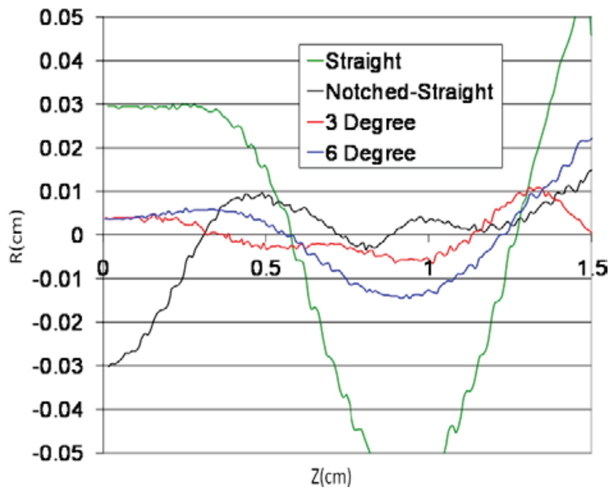

Figure 8. Inner surface profile of the liner at impact radius for different glide-plane configurations. The selected configuration will be a notched-straight configuration shown in Figure 1.

VI. TARGET SIMULATIONS

In cylindrical geometry with a shock wave converging radially upon the axis, the shock wave will tend to accelerate and when that shock breaks out, the free surface velocity will also tend to accelerate towards the axis. The free surface velocity of course is the measured variable in this experiment (shock velocity is also measured but from shock arrival at the free surface indicated by the velocimetry data) and so the effect of the geometry will be very important in interpreting the results of our experiment. To illustrate the difference between planar shock experiments and a cylindrically imploding shock, Figure 9 was generated from two simulations using impactors at the same velocity in planar and cylindrical geometry. There is a dramatic difference in the free surface velocities and it is clear that there is also an effect on the shock arrival time.

For the configuration we are proposing, the 1-D MHD simulations described earlier were used to study the impact with the target and generate a self-consistent description of the entire experiment based upon the fundamental simplifications in the circuit model. The free surface velocities for our proposed target are presented in Figure 10 showing a free surface velocity of more than 27 km/s. The notch at the front of the step is believed to be caused by the EOS but further investigation is needed to determine the definite cause. These simulations also clearly show the acceleration of the free surface velocity, possibly complicating the measurement of the actual free surface velocity. With the liner impacting at 23 km/s, this free surface velocity is significantly higher than what would be expected in a planar geometry.

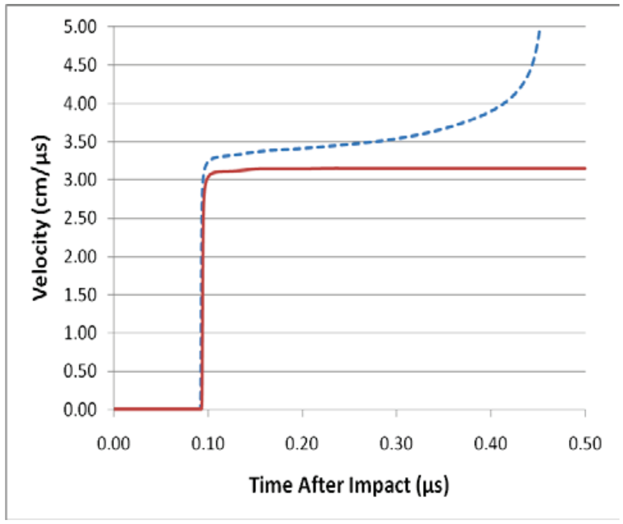

Figure 9. Difference between cylindrical and planar geometries using identical impactors at the same velocity.

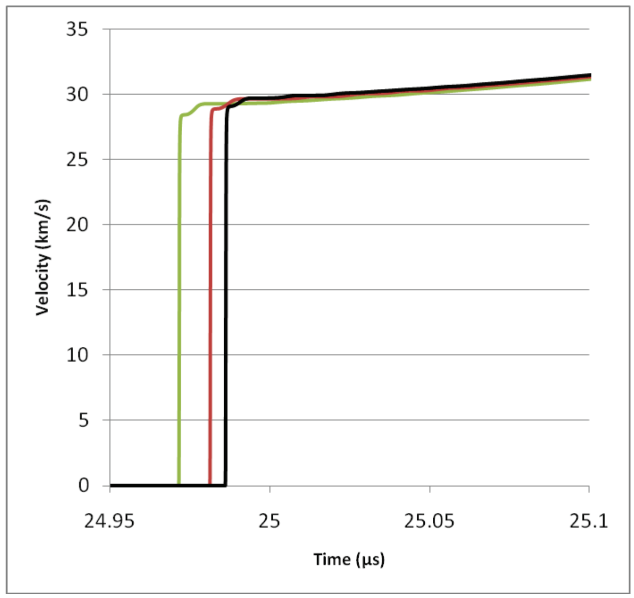

Figure 10. Free surface velocities of target steps from 1-D MHD simulations. Green is 0.4-mm thick step, red is 0.6-mm, and black is 0.7-mm.

The shock velocity and particle velocities achievable in this experiment we expect to be on the order of 20 km/s and 12 km/s respectively, showing that the free surface velocity is much higher than twice the particle velocity. This shock velocity corresponds to a compression of approximately 2.5 fold at pressures near 0.7 TPa. Figure 11 shows the phase diagram for the target as points connected by lines where the points are 0.5 ns apart. the black line represents the outer surface in contact with the imploding liner and the magenta line near the vapor dome represents the free surface. The treatment of the impacted surface is a bit anomalous because there is actually a Lagrangian vacuum cell between the flyer and the target.

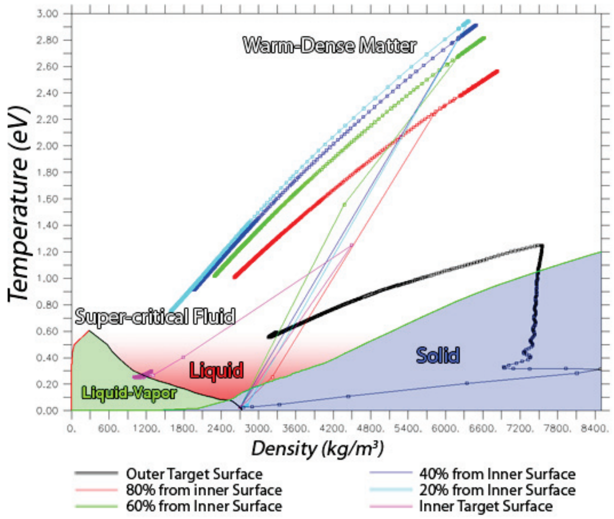

Figure 11. Phase diagram for various parts of the target. The black line/points represent the outer surface, and the magenta line/points near the vapor dome represent the inside surface with red, green, blue, and teal moving from the outside towards the axis.

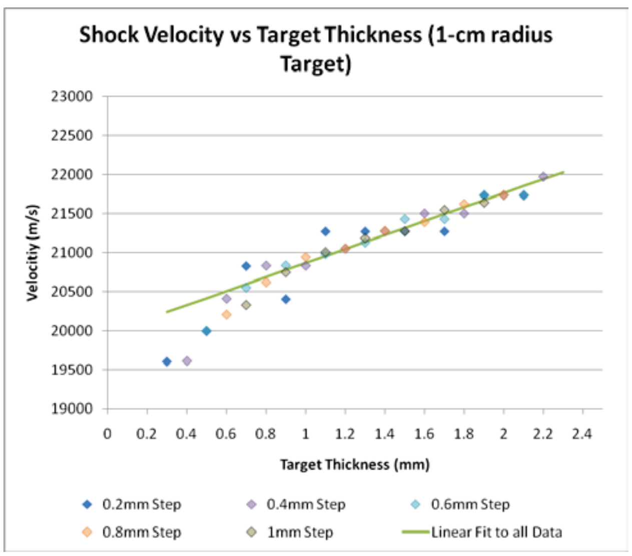

Figure 12. Calculations of shock velocity based off of twelve different 1-D simulations from 0.2-mm thick targets to 2.4-mm thick targets. All targets have an outer radius of 1 cm.

The phase diagram shows that the shocked aluminum will be far past the point of melting and will lie in the warm-dense matter region. Also, we see that after the shock hits, there is a period of isentropic compression inside the target before releasing along the same isentrope when the rarefaction wave passes. There also appears to be the possibility that the free surface will contain a mixture of liquid and vaporized aluminum, perhaps creating problems for the PDV laser.

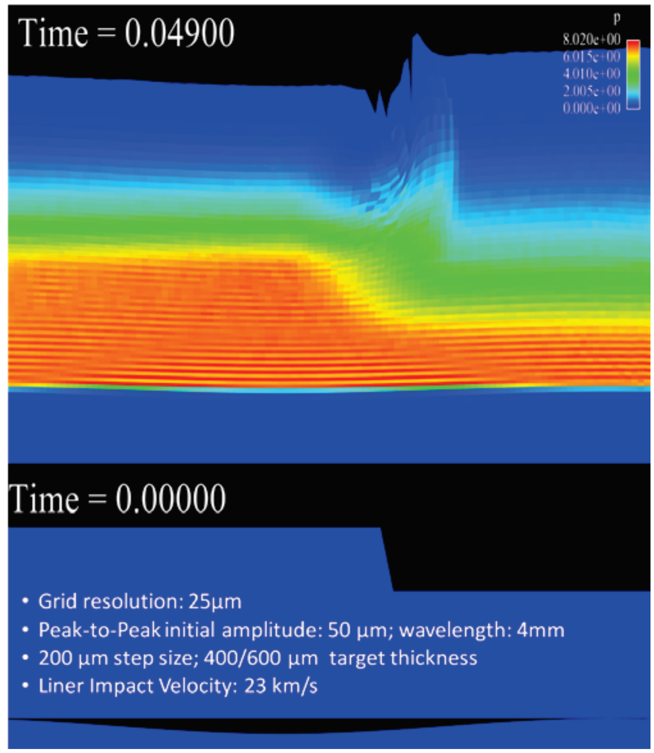

Figure 13. 2-D hydrodynamic simulation of liner impacting target in R-Z space. The vertical axis is negative radius, and the horizontal axis is in z. The colored axis represents pressure from 0 to 8 MPa and the time is measured in μs after impact.

From the 1-D simulations, we can also quantify the accelerating shock. Performing multiple 1-D simulations using different target thicknesses allows us to measure a shock velocity based upon shock arrival time at a free surface (this is determined as the time of greatest acceleration on that free surface). Arbitrarily picking a number of different target thicknesses and calculating the shock velocity between various inner and outer radii, we can analyze shock velocity as a function of target thickness. This is illustrated in Figure 12 and clearly shows the increasing shock velocity as the shock moves inward. The spread in the points indicates the uncertainty in determining shock breakout given a fixed sampling interval of 0.5 ns.

In addition to the 1-D MHD simulations, 2-D Lagrangian hydrodynamics simulations were performed in order to understand the behavior of the free surface on a stepped target and simulate the effects of a perturbed liner impacting the target. Because the 2-D code does not allow us to fully simulate the liner dynamics, we used the impact velocity from the 1-D simulations and initialized the liner at that velocity while in contact with the target. As a result, density, velocity, and temperature gradients present within the liner at impact were not taken into account. A grid resolution of 25 μm was used in the simulations because a finer resolution would not have run for as long as needed before the mesh would tangle. Some mesh tangling was avoided by merging two cells at the corners of the steps to form five-node rectangular cells. The initial perturbation along the inside surface of the liner was generated to mirror the previous results obtained from 2-D MHD liner calculations shown in Figure 8. The results of this simulation are presented in Figure 13 and show a slight tilt in the free surface that is seen in the free surface velocity traces. This could impact the PDV results and rather than giving a defined free surface velocity, the PDV may give a bracket of velocities in that region. The uncertainty also means that shock breakout is harder to accurately determine and the uncertainty in the shock velocity will be increased. These uncertainties are quantified in Figure 14 showing an uncertainty in free surface velocity of 0.65%. When the uncertainty in shock arrival time is measured and then propagated through a calculation of the shock velocity, the error associated with the shock velocity is 1.15%. As one of the goals of this experiment is to perform a highly accurate measurement of a point along the shock Hugoniot, understanding these sources of error is important.

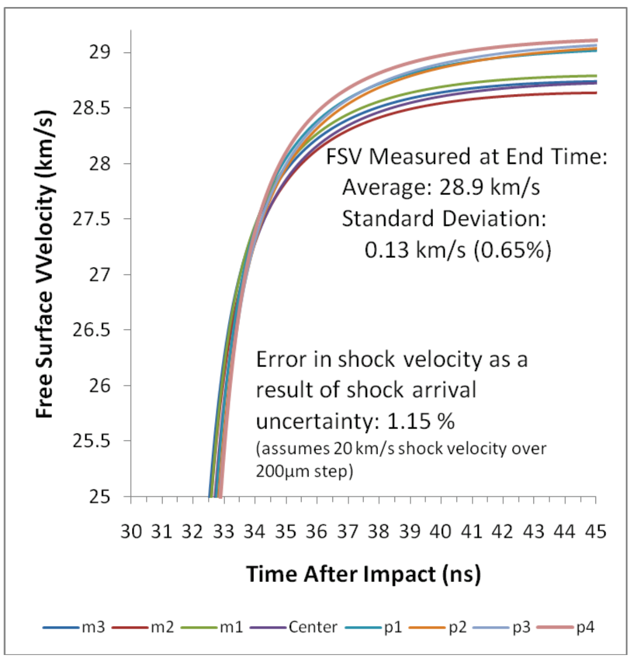

Figure 14. Free surface velocity profiles for seven different nodes at the center of the step. This reflects the variety of measurements taken over a 150 µm spot size on the surface.

VII. CONCLUSIONS

The proposed experiment design and supporting calculations are presented for the ALT-3 experiment. A circuit model composed of simple circuit elements is presented and shown to give a reasonable approximation for the DEMG driver. Using this circuit model, 1-D MHD calculations were performed to simulate the liner performance and impact into the target. 1-D calculations also show a significant difference between traditional planar shock experiments and experiments in converging cylindrical geometry. From these simulations we find that the particle velocity cannot be inferred as half the free surface velocity and we also find that the shock velocity is accelerating. The phase diagram for the target shows that the target will be shocked into the warm dense matter regime and isentropically compressed as the shock moves inward. Given 2-D simulations of the imploding liner, the axial perturbations along the inner radius of the liner have been characterized and in 2-D hydrodynamics calculations the effect these perturbations might have on measurement uncertainty has been presented. A given peak-to-peak perturbation amplitude of 50 µm is translated into a 0.65% effect in the free surface velocity and a 1.15% effect tin the measurement of the shock velocity. Tentatively, the experiment is scheduled to be conducted in Sarov, Russia in the spring/summer of 2012.

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